UDC 621
DOI: 10.15587/1729-4061.2024.298202

A COMPARATIVE ANALYSIS OF GAS-COOLED FAST REACTOR USING HETEROGENEOUS CORE CONFIGURATIONS WITH THREE AND FIVE FUEL VARIATIONS

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GFR or Gas-cooled Fast Reactor is one type of fast generation-IV that uses a very high cooling temperature. Thus, it is necessary to have the right reactor core design so that the power distribution of neutrons produced reaches a safe and even limit point. The use of a uniform (homogeneous) reactor core can produce peaking power. This is very avoidable because it will cause a reactor accident. In this study, researchers tried to compare the results of the analysis for two heterogeneous reactor core designs including the configuration of 3 fuel variations and 5 fuel variations using UN-PuN fuel. This study aims to determine the k_{eff} value produced by both types of fuel variations during 5 years of burn-up and determine the characteristics of neutron flux, fission rate, and fission product during 15 years of burn-up. This study was started by calculating the homogeneous and heterogeneous core of 3 and 5 fuel variations with neutron transport simulation involving OpenMC. The calculation results show that the heterogeneous core configuration of 5 fuel variations for the k_{eff} value is more optimal than 3 fuel variations, because it has the smallest excess reactivity value. The neutron flux and fission rate characteristics for 5 fuel variations are more evenly distributed when compared to 3 fuel variations to maintain neutron lifetime and reactor life in operation. Burn-up residual plutonium material and minor actinide waste for 5 fuel variations have less mass than 3 fuel variations. The results of neutronic analysis of GFR reactors with heterogeneous reactor core designs for 5 fuel variations are better in terms of reactor criticality, neutron power distribution, and waste produced. Finally, optimization of the UN-PuN fuel volume fraction of 60 % provides the optimal k_{eff} value

Keywords: comparative, fuel variations, Gas-cooled Fast Reactor, heterogeneous, k_{eff}, reactor core

Received date 15.11.2023
Accepted date 30.01.2024
Published date 28.02.2024

How to Cite: *Prasetya, F., Syarifah, R. D., Karomah, I., Aji, I. K., Trianti, N. (2024). A comparative analysis of gas-cooled fast reactor using heterogeneous core configurations with three and five fuel variations. Eastern-European Journal of Enterprise Technologies, 1 (8 (127)), 6–17. doi: https://doi.org/10.15587/1729-4061.2024.298202*

1. Introduction

Lately, nuclear energy sources have been widely studied by researchers, especially in Indonesia. Nuclear energy is a new alternative with a significant enough electrical power production capability. Nuclear energy is produced from fission reactions by fuel that occur in vessel reactors by the NPP (Nuclear Power Plant). NPP is power plants that use one or more nuclear reactor units to produce steam that has pressure to drive generator turbines [1]. The combustion process does not release smoke particles containing harmful compounds, such as CO_2, SO_2, and NO, so it does not produce carbon emissions. It can create the country's goal of net zero emissions [2]. The development of nuclear reactors began in 1950 and is divided into five generations, including generations I, II, III, III+, and IV [3]. Generation IV is a development of reactor innovations from the previous generation that are the most advanced, have a longer operating life, and put forward advanced reactor systems. One type of generation IV reactor system that is still in the development stage is the GFR reactor [4].

GFR reactors use fast neutron spectrum, actinide recycling, and a closed cooling cycle [5]. This reactor uses fast neutrons in carrying out fission reactions. The fission reaction splits heavy atomic nuclides into lighter ones and produces 2–3 neutrons [6]. In addition, the fission reaction also produces gamma radiation and energy of 200 MeV. The coolant used is helium (He), which has the characteristics of one phase, is chemically inert, has a reasonable neutron absorption rate, and can operate with outlet temperatures up to 850 °C. High temperatures make it possible to produce hydrogen gas as alternative energy in the form of electrical energy. GFR reactor fuel used in this study is a mixture of fissile and fertile material in uranium-plutonium nitride with a melting point of up to 2,500 °C [7].

The use of high temperatures, especially in reactor fuels and coolants, affects the rate of neutron production and fission reactions that occur. This is related to the use of GFR reactor core design, so that the resulting temperature is in accordance with safe limit standards. This is an important subject for GFR reactor researchers in making reactor core designs with high standards of safety. The GFR reactor core concept has been widely developed, especially in projects in Europe [8]. The development includes the idea of using silicon cladding of carbide plates in fuels arranged like honeycomb structures or commonly referred to as the hexagonal lattice designs [9, 10].

GFR reactors generally use a hexagonal lattice design consisting of homogeneous and heterogeneous core configurations. The homogeneous reactor core uses the same fuel percentage composition, while heterogeneous uses a different fuel percentage composition in each region. The configuration of the heterogeneous core has a lower neutron flux distribution than the homogeneous core. The resulting fission reaction is more even, thus minimizing the peaking power in the reactor core [11]. However, further studies need to be made for the use of the heterogeneous core with certain variations (more than 2 fuel variations) to produce a more even distribution of neutron flux and a more stable level of criticality ($k_{eff} \approx 1$). The development of heterogeneous core structure variations can be carried out in the plane of the radial direction GFR reactor (*XY* axis). Therefore, the development of the use of heterogeneous core designs in GFR reactors is relevant for further research.

2. Literature review and problem statement

The paper [12] presents the results of research on the use of GFR homogeneous reactor core assembly design with two geometries, i.e. hexagonal and rectangular. The results show that the use of hexagonal and rectangular geometry has a similar trend pattern of k_{inf} charts. But there were unresolved issues related to this research that it is only limited to calculating the criticality of a simple reactor (k_{inf}), without paying attention to neutron leaks that occur inside the reactor core.

The paper [13] presents the results of research on the effect of using homogeneous and heterogeneous cores on reactor criticality values (k_{eff}). The research used the FI-ITB-CHI program with a reactor power of 500 MWTh. The results show that the percentage of Pu 11 % provided the most stable criticality value by using homogeneous cores and fuel volume fraction of 60 %. The researchers then used the heterogeneous core by varying the percentage of Pu in the *F*3 region (*F*1 and *F*2 are constant). The result obtained is the most stable criticality level at the percentage of Pu of *F*1=8 %, *F*2=10 %, *F*3=14 %. But there were unresolved issues related to this research that it only focuses on variations in the percentage of Pu in the *F*3 region, so additional variations are needed for *F*2 and *F*3 to get more varied data.

The paper [14] using the SRAC-COREBN simulation program with the JENDL 4.0 nuclear library obtained average power density values and maximum power density that tended to exceed limit values. The average power density is 70 Watt/cc and the maximum power density is 100 Watts/cc. The results show that the use of Pu-239 material with a percentage of 8 % (homogeneous) provides an average power density value of 75.03 Watt/cc and a maximum power density value of 107.4 Watt/cc. Meanwhile, for the percentage of Pu-239 of *F*1=7.5 %, *F*2=8 %, *F*3=8.5 % (heterogeneous), an average power density value of 69.75 Watt/cc and a maximum power density value of 95.14 Watt/cc were obtained. But there were unresolved issues related to this research that the design still has a negative excess reactivity, so there needs to be additional analysis in the form of variations in fuel volume fractions.

The paper [15] discusses the comparison of power distribution (Watt/cc) for reference cores and flattening cores in GFR reactors. The reference core uses a homogeneous fuel array with a percentage of 65 %. As for the flattening core, it uses a heterogeneous fuel arrangement, which is divided into 3 zones with a percentage of 55 %, 60 %, and 65 %. The results showed that flattening terraces produce an average power density and a lower maximum power density, so as to minimize peaking power. But there were unresolved issues related to this research that the resulting power density value is still not in accordance with the threshold limit value, so further analysis is needed.

The paper [16] analyzes the use of variations in heterogeneous core fuel fractions of GFR reactors. This study used fuel fractions with different radii and heights per case. The results of this study show that the most optimal heterogeneous core is found in a design with a radius of *F*1:*F*2:*F*3=50 cm:30 cm:30 cm, height *F*1:*F*2:*F*3=50 cm:40 cm:30 cm, and the percentage of Pu in *F*1:*F*2:*F*3=7 %:10 %:13 %. The k_{eff} value obtained is 1.101883. But there were unresolved issues related to this research that it is still necessary to add 0–5 % Pu weapon grade to get a more optimal k_{eff} value.

The paper [17] analyzed the flux distribution of homogeneous reactor core models on *XY* and *YZ* axis displays using the MCNP6 program. The results show that the highest flux results are achieved in the center of the core for the *XY* and *YZ* axis display using 100 % fresh fuel. But there were unresolved issues related to this research that it still uses homogeneous fissile content (no variation in fissile content) and simple configuration, so there is no even neutron flux spectrum.

Furthermore, the paper [18] also tried to identify neutron flux distributions for two reactor core configurations, including homogeneous and heterogeneous core. The simulation program used is OpenMC. The homogeneous core uses a percentage of Pu of 10 % and the heterogeneous core *F*1=9 %, *F*2=10 %, *F*3=11 %. The results show that the peak of neutron flux with BOL (Beginning of Life) conditions for homogeneous cores reaches 2.4×10^{10} neutrons/cm^{2}s and heterogeneous 2.1×10^{10} neutrons/cm^{2}s. The heterogeneous core value is lower because the fission reaction that occurs can be distributed evenly for all fuel components used. This is an important parameter for the reactor safety system. But there were unresolved issues related to this research that the neutron flux value still tends to be small for a reactor power of 300 MWth.

A way to overcome these difficulties can be to perform a more detailed neutronic analysis for several heterogeneous reactor core designs, including 3 fuel variations (*F*1–*F*3) and 5 fuel variations (*F*1–*F*5). This approach was used in the literature [12–15]. All this suggests that it is advisable to conduct a study on the use of heterogeneous reactor core designs that conform to predetermined parameters and specifications. The hope is to obtain the most optimal results in terms of fissile content, criticality, and power distribution, and neutron flux distribution.

3. The aim and objectives of the study

The aim of the study is to determine the neutronics analysis of heterogeneous core design with a certain amount of fuel variation by the comparison method. This will make it possible to obtain the best and most secure heterogeneous core design.

To achieve this aim, the following objectives are accomplished:

– to calculate the reactor criticality level (k_{eff} value) of the heterogeneous core with 3 fuel variations and 5 fuel variations in the GFR reactor fueled by UN-PuN;

– to determine the characteristics of neutron flux, fission rate, and fission product of the heterogeneous core with 3 fuel variations and 5 fuel variations in GFR reactors fueled by UN-PuN;

– to determine the percentage of fuel volume fraction according to the desired criticality.

4. Materials and methods

4. 1. Research procedures

The object compared in this research is a heterogeneous core design of 3 fuel variations ($F1$–$F3$) and 5 fuel variations ($F1$–$F5$). This research focuses on neutronic analysis including k_{eff} value, neutron flux, fission rate, and fission product. Optimization of fuel volume fraction variations needs to be done at the end of the calculation to prove the percentage of fuel used is in accordance with the desired k_{eff} value. This research uses the OpenMC 0.13.0 Monte Carlo simulation program with ENDF B-VII/1 nuclear data library.

The homogenous core consists of 11 cases with the percentage of plutonium fuel varying by 5–15 %. The most optimal percentage of the homogeneous core is used as a reference for designing a heterogeneous core. For heterogeneous cores, two types of configurations, i.e. 3 fuel variations and 5 fuel variations, will be compared and analyzed for differences during 5 years of burn-up. To see the ability of the GFR reactor to maintain fission reactions, an extended burn-up period of up to 15 years. Furthermore, analysis was carried out using reactor criticality value (k_{eff}), neutron flux, fission rate, and fission product. Finally, to see the fraction of reactor fuel volume suitable for this study, a variation of 5 cases was carried out with a range of 45–65 %. The research procedure for calculating homogeneous core, heterogeneous core 3 and 5 fuel variations is fully described in Fig. 1.

The OpenMC 0.13.0 program basically uses Monte Carlo calculations and applies the neutron transport equation or the Boltzmann equation [19]. Neutron transport serves to determine the distribution and population of neutrons so that the fission chain reaction can be maintained and stable. The neutron transport equation is shown in equation (1)–(3) [20]:

$$\frac{1}{V}\frac{\partial}{\partial t}\phi(r,E,\Omega,t)+\Omega\nabla\phi(r,E,\Omega,t)+ +\Sigma_t(r,E,t)\phi(r,E,\Omega,t)=Q_s(r,E,\Omega,t)+Q_f(r,E,\Omega,t); \quad (1)$$

$$Q_s(r,E,\Omega,t)= =\int_{4\pi}\int_0^\infty \Sigma_s(r,E\leftarrow E',\Omega\leftarrow\Omega',t)\phi(r,E',\Omega',t)\mathrm{d}E'\mathrm{d}\Omega'; \quad (2)$$

$$Q_f(r,E,\Omega,t)= =\frac{1}{4\pi}\sum_{j=1}^{j}\chi_j(E)\int_0^\infty v\Sigma_{f.j}(r,E',t)\phi(r,E'',t)\mathrm{d}E'. \quad (3)$$

The results of cross section calculations generated from OpenMC simulations have units [particle-cm/source]. While the output data of neutron flux distribution and fission rate have successive units, i.e. [particle/cm^{2}s] and [particle/s]. The calculation result needs to be normalized (f) to adjust the units of the output data. The normalization factor formula is shown in the following equation (4):

$$f=\frac{Pv}{Qk_{eff}}, \quad (4)$$

where f – normalization factors (source/s); P – system power (J/s); v – neutrons rate (neutrons/fission); Q – the energy produced per fission reaction (J/fission); k_{eff} – effective multiplication factor (neutrons/source).

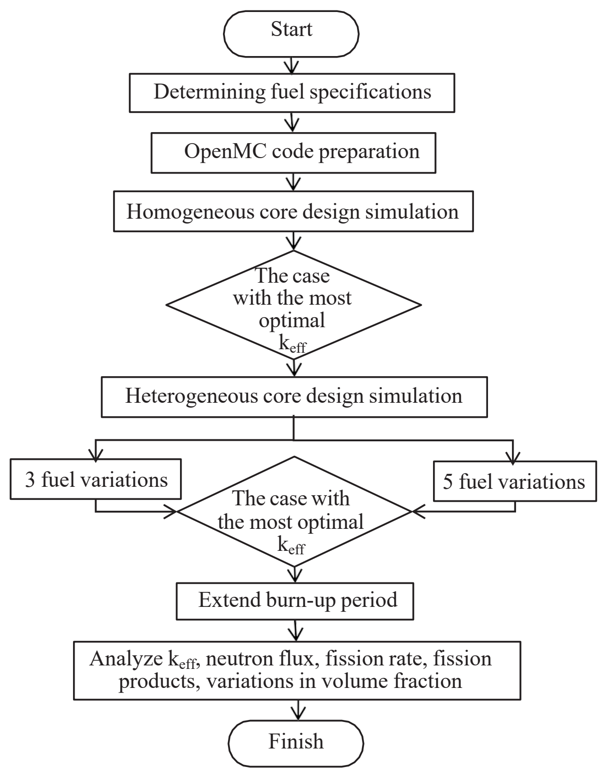


Fig. 1. Research design flow diagram

The core of the GFR reactor consists of a fuel composition presented in the form of a percentage of the mole fraction. Mole fractions cannot be used in OpenMC programs so conversion to weight fractions is necessary. The formula for converting mole fraction (mol %) to weight fraction (wo) is as follows:

$$m_{element}=Mr_X\times mol_X, \quad (5)$$

$$wo=\frac{m_{element}}{m_{total}}, \quad (6)$$

where $m_{element}$ – the mass of each element; Mr_X – relative atomic mass of atom X; mol_X – mole fraction percentage (%); wo – weight fraction; m_{total} – the total mass of each element.

The criticality value of the reactor is calculated using the effective multiplication factor (k_{eff}). The k_{eff} value is the ratio of neutrons resulting from the fission reaction of one generation to the number of neutrons lost due to absorption reactions and leakage in the previous generation [21]. The effective multiplication factor can also be expressed mathematically in the six factor formula in equation (7):

$$k_{eff} = \varepsilon L_f \rho L_t f \eta, \tag{7}$$

$$\Delta k / k = \frac{k_{eff} - 1}{k_{eff}} \times 100\,\%, \tag{8}$$

where ε – fast fission factor; p – resonance capture probability; f – thermal utilization factor; η – thermal utilization factor; L_f – probability of fast non-leakage; L_t – probability of thermal non-leakage.

If the k_{eff} value=1, then the reactor is in a critical condition. Meanwhile, if the k_{eff} value is <1, the reactor is in a sub-critical condition and k_{eff}>1, the reactor is in a super-critical condition. The criticality of the reactor can also be assessed using the excess reactivity ($\Delta k/k$) equation shown in equation (8). Reactivity is more of a magnitude of reactivity that exceeds a certain criticality constant in the reactor core.

4. 2. Fuel parameters and specifications

This research uses a mixture of UN-PuN fuel arranged in a circle to form a pin design and hexagonal prism assembly pelletized fuel coated with cladding and coolant. The uranium material used comes from nature consisting of Uranium-235 and Uranium-238 with a content of 0.7 % and 99.3 %. The plutonium material comes from LWR waste, which has been burnt up at 33 GWd/ton. The plutonium material consists of several isotopes, including Pu-238, Pu-239, Pu-240, Pu-241, and Pu-242. Each isotope has a content of 1.8 %, 58.7 %, 24.2 %, 11.4 %, and 3.9 % [22].

The nitride material always binds to the U-Pu material to improve the fuel breeding ratio in the fast reactor. The fuel is coated with cladding derived from Silicon Carbide (SiC) material. This material has advantages, including having high mechanical strength. Between the fuel and the cladding, there is a space in the form of a gap filled with helium gas. The gap provides space for reactor fuel because the expansion process occurs as the fission reaction progresses. In addition, the fuel is surrounded by a coolant in the form of helium gas to optimize fast neutron absorption to keep the reactor in a critical condition until the end of combustion. The parameters and specifications of the fuel used are described in Table 1 below.

The fuel geometry in the GFR reactor is hexagonal. This form is commonly used in fast reactors because it can maximize fast neutrons in fission reactions. The inlet temperature used is 674 K. The thermal power of the reactor used tends to be low because the GFR reactor used is of the SMR (Small Modular Reactor) type. SMR is widely used by researchers because it is effective in its application. SMR is designed to produce electrical energy up to 300 MW, which components and systems can be assembled in the workshop forming a module. The modules are transported and installed upon request [23]. SMR design can achieve better results in terms of safety and operational costs [24].

Table 1

Fuel parameters and specifications

Parameter	Specification
Fuel	UN-PuN
Fuel density	14.3 (gr/cm^3)
Fuel shape	Pellet
Fuel volume fraction	45–65 %
Gap volume fraction	0.5 %
Cladding volume fraction	10 %
Coolant volume fraction	24.5–45.5 %
Gap forming material	Helium (He)
Cladding forming material	Silicon Carbide (SiC)
Coolant forming material	Helium (He)
Uranium volume fraction	85–95 %
Plutonium volume fraction	5–15 %
Pin pitch	1.45 cm
Assembly pitch	17.04 cm
Pin and assembly geometry	Hexagonal prism
Reactor power	300 MWth
Active core type	Cylinder pancake
Temperature	674 K

4. 3. Fuel pin and assembly configuration

The fuel pins used are 127 in one assembly. The active core of the GFR reactor contains 127 fuel assemblies composed of several types of rings, including the inner ring, ring n, and outer ring. Ring n is found using the arithmetic formula $a+(n-1)b$. The value of a represents the number of first rings, and b is the ratio of the number of second rings to the first ring. The pin pitch is obtained from the sum between the outer radius of the fuel, gap, cladding, and coolant. Meanwhile, the assembly pitch is obtained from the sum between the outer radius of the fuel, which is composed of several types of rings in one assembly. The fuel pin configuration is shown in Fig. 2 below.

The pellet-shaped fuel pin has a size of 0.562 cm. The gap (helium) between the fuel pin and cladding aims to provide free space for fuel in the event of expansion. The coolant (helium) in this reactor has the characteristics of absorbing neutrons well, phase unchanged, and not radioactive.

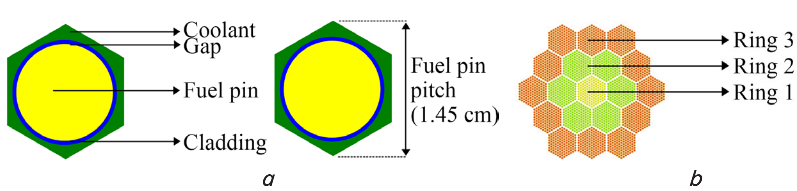
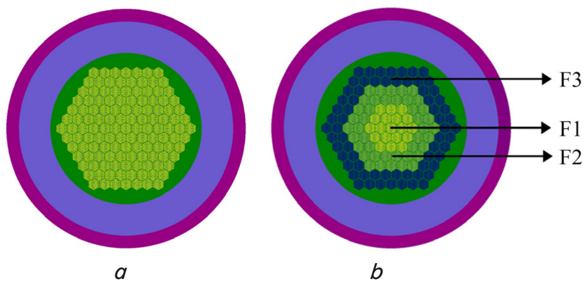


Fig. 2. Fuel pin and assembly: *a* – fuel pin configuration; *b* – arrangement of fuel pin rings in one fuel assembly

4. 4. Reactor core configuration

The fuel configuration contained in the GFR reactor core is arranged homogeneous and heterogeneous shown in Fig. 3. The homogeneous core uses the same percentage volume of plutonium in each ring assembly. Meanwhile, heterogeneous cores use different volumes of plutonium in each ring assembly. Heterogeneous cores generally involve more than one variation of fuel fraction. The study used two types of heterogeneous designs: 3 and 5 fuel variations. If using 3 fuel variations (*F*1–*F*3), the average is taken from the percentage of plutonium used. It applies to 5 fuel variations (*F*1–*F*5).



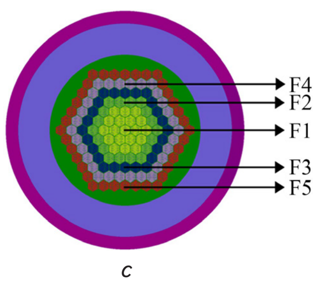


Fig. 3. Core configurations:
a – homogeneous reactor core; *b* – heterogeneous reactor core with 3 fuel variations; *c* – heterogeneous reactor core with 5 fuel variations

In the heterogeneous core design with 3 fuel variations, there are 3 regions that have different Pu compositions. The heterogeneous core of 3 fuel variations has a combination of 3:2:2, which is divided into region 1 (F1) 3 rings, region 2 (F2) 2 rings, and region 3 (F3) 2 rings. The heterogeneous core of 5 fuel variations has a combination of 3:1:1:1:1, which is divided into region 1 (F1) 3 rings, region 2 (F2) 1 ring, region 3 (F3) 1 ring, region 4 (F4) 1 ring, and region 5 (F5) 1 ring.

4. 5. Gas-cooled Fast Reactor design

The reactor core type is Small Modular Reactor (SMR) in the form of a pancake cylinder. The active core is coated by the reflector and absorber materials axially (top-down) and radially (circular). The diameter and height of the reactor core are respectively 200 cm and 120 cm. The diameter and height of the reflector are respectively 100 cm and 80 cm. The diameter and height of the absorber are respectively 40 cm and 30 cm. The reactor core design is shown in Fig. 4 below.

The reflector material is SiC, which has an albedo percentage of 85.17 % [25]. Albedo is the number of neutrons reflected by a reflector surface. Meanwhile, the absorber comes from boron carbide (B4C) material, which has high hardness properties, stability at high temperatures, and good neutron absorption ability [26]. Reflector and absorber materials have a density of 3.210 gr/cm^3 and 2.52 gr/cm^3 [27].

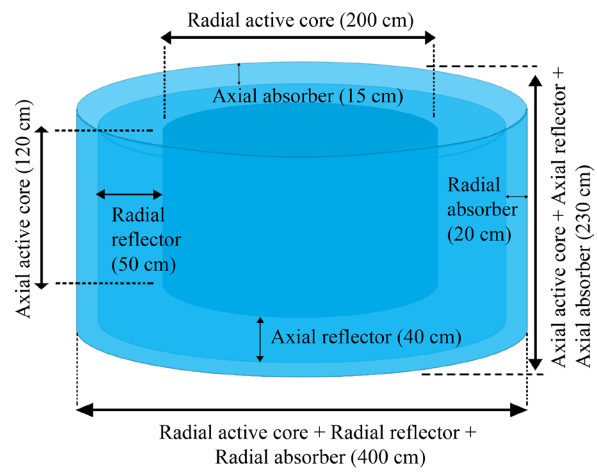


Fig. 4. Design of gas-cooled fast reactor

5. Results of neutronic analysis of heterogeneous core designs with 3 and 5 fuel variations using the comparison method

5. 1. Reactor criticality level (k_{eff} value) of the heterogeneous core with 3 and 5 fuel variations in the GFR reactor fueled by UN-PuN

The results of the homogeneous core calculation are visualized as a graph of the burn-up time relationship with the value of the effective multiplication factor (k_{eff}) in Fig. 5.

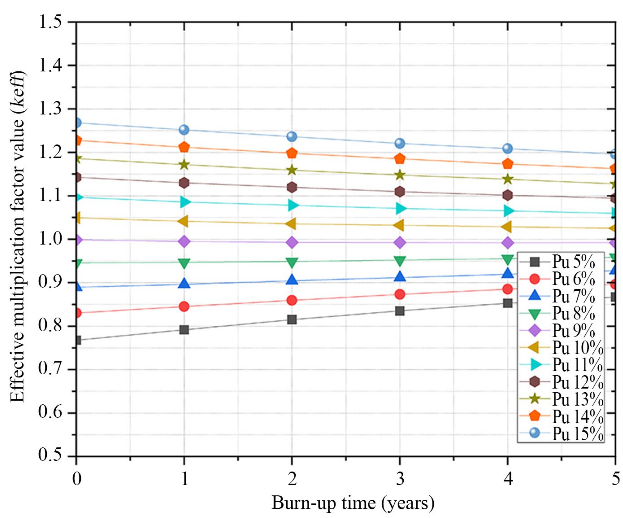


Fig. 5. The criticality value of the homogeneous core

The results of data with the most optimal and stable k_{eff} value are shown on the graph of plutonium fuel composition of 10 %. Plutonium, with a percentage of 10 %, has a k_{eff} value at the beginning of the burning year of 1.0495 and the end of the burning year of 1.0255. The excess reactivity values for the beginning and end of combustion were 4.74 % and 2.48 %. Optimal conditions are shown at criticality values close to 1 until the end of burn-up, while stable conditions are seen in the flattest chart trend. A percentage of 5 % plutonium indicates a k_{eff} value with sub-critical conditions. A percentage of 15 % plutonium signifies a k_{eff} value with super-critical conditions. The greater the percentage of plutonium used, the greater the k_{eff} value. Based on the results of criticality values, chart trends, and excess reactivity, it can be concluded that the percentage of 10 % plutonium can be used as a reference for further calculations in the form of heterogeneous core configurations.

Heterogeneous cores have more than one variation in the composition of plutonium fuel. The heterogeneous core for this study consists of two fuel variations, i.e. 3 fuel variations (*F*1–*F*3) and 5 fuel variations (*F*1–*F*5). The geometric arrangement of the ring for the three fuel variations consists of *F*1 placed in the middle of the core, *F*2 placed between *F*1 and *F*3, and *F*3 located on the edge of the reactor core (adjacent to the reflector). The geometric arrangement of the ring for 5 fuel variations consists of *F*1 placed in the middle of the reactor core, *F*2 placed after *F*1, *F*3 placed after *F*2, *F*4 placed after *F*3, and *F*5 placed on the edge of the reactor core. The fission chain reaction for each fuel variation is related to the combined percentage of plutonium used in each ring. Plutonium percentage data for each fuel variation are in Tables 2, 3 below.

Table 2

Percentage of heterogeneous core plutonium for 3 fuel variations

Case	Percentage of plutonium			Mean
	*F*1 (3 rings)	*F*2 (2 rings)	*F*3 (2 rings)	
1	7.5 %	10 %	12.5 %	10 %
2	7 %	9 %	14 %	10 %
3	7 %	10 %	13 %	10 %
4	7 %	11 %	12 %	10 %
5	8 %	10 %	12 %	10 %

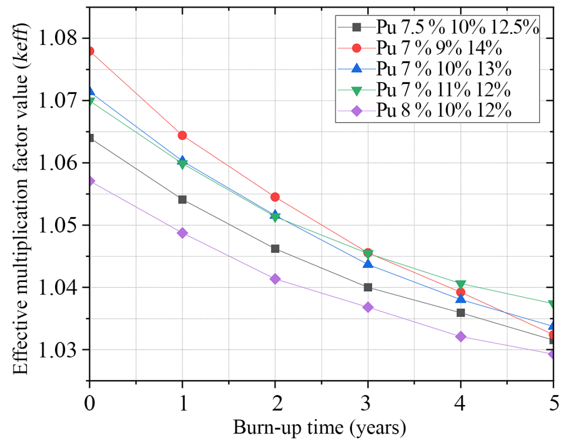
Table 3

Percentage of heterogeneous core plutonium for 5 fuel variations

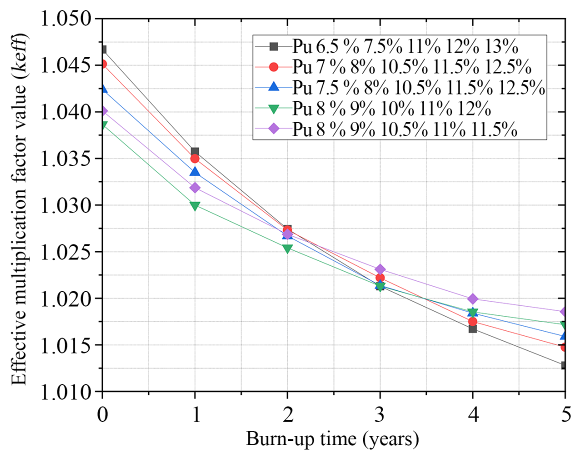
Case	Percentage of plutonium					Mean
	*F*1 (3 rings)	*F*2 (1 ring)	*F*3 (1 ring)	*F*4 (1 ring)	*F*5 (1 ring)	
1	6.5 %	7.5 %	11 %	12 %	13 %	10 %
2	7 %	8 %	10.5	11.5 %	13 %	10 %
3	7.5 %	8 %	10.5	11.5%	12.5 %	10 %
4	8 %	9 %	10 %	11 %	12 %	10 %
5	8 %	9 %	10.5 %	11 %	11.5 %	10 %

The five cases for 3 and 5 fuel variations have an average value of 10 %, taken from the most stable homogeneous core data reference criticality. The percentage of plutonium used for 3 fuel variations and 5 fuel variations has a strategy for determining its composition. When viewed in Tables 2, 3, each fuel variation has a difference value between the percentage of volume fractions that are not too far. For example, data on 3 fuel variations for *F*1=8, *F*2=10, and *F*3=12 have a difference value of 2. Meanwhile, 5 fuel variations for *F*1=8, *F*2=9, *F*3=10, *F*4=11, *F*5=12 have a difference value of 1. It aims to avoid the composition of excess or reduced plutonium in certain areas in the reactor core.

The criticality value (k_{eff}) results for heterogeneous core designs of 3 fuel variations and 5 fuel variations are shown in Fig. 6. These two designs have significant differences for the k_{eff} value parameters reviewed during 5 years of combustion. The 5 fuel variations has a more optimal k_{eff} value than the 3 fuel variations. This shows that heterogeneous designs with a greater amount of variations can reduce excess reactivity values and k_{eff} values to close to 1.



a



b

Fig. 6. The criticality value:
a – heterogeneous core criticality value of 3 fuel variations;
b – heterogeneous core criticality value of 5 fuel variations

An optimal reactor can maintain fission capability until the combustion period ends. The low-power GFR reactor with Small Modular Reactor (SMR) type can operate for over 20 years [28]. The reference data of 3 fuel variations and 5 most optimal fuel variations are recalculated by extending the burn-up period to 15 years. The calculation results are shown in Fig. 7 by producing different graphic patterns between the two heterogeneous core configurations.

Based on Fig. 7, year 0 to year 5 in the burning phase of the k_{eff} chart decreased significantly. Year 5 to year 15 in the breeding phase of the k_{eff} chart tends to be smoother. It shows the decay phase of U-238 to Pu-239 to maintain the k_{eff} value until the end of combustion. A good breeding process in fuel characterizes the nature of GFR reactors with a fast neutron spectrum. The criticality analysis (k_{eff}) can only review reactors in sub-critical, critical, or super-critical states. We cannot see whether the neutron distribution and fission reaction inside the reactor core are working optimally or not. Therefore, it is necessary to analyze the neutron flux distribution, fission rate, and fission product to measure the level of reactor safety comprehensively.

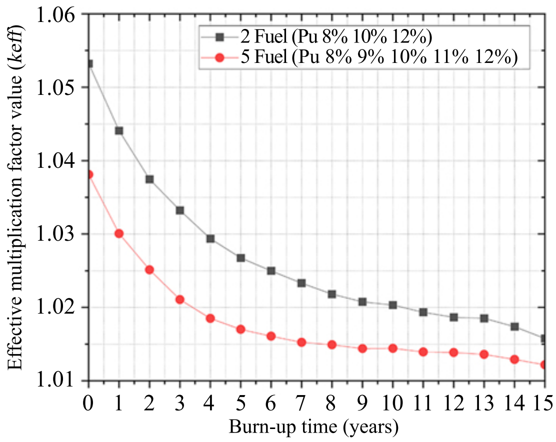


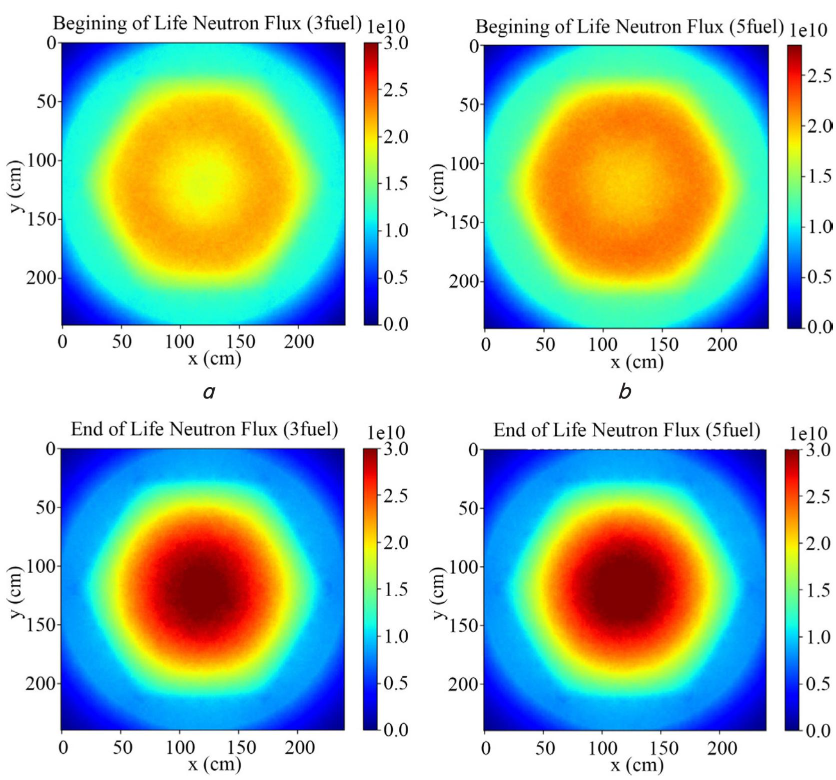
Fig. 7. The criticality value of the extended burn-up heterogeneous core

5. 2. Characteristics of neutron flux, fission rate, and fission product of the heterogeneous core with 3 fuel variations and 5 fuel variations in GFR reactors fueled by UN-PuN

The movement of neutrons per unit area per second (neutrons/cm^{2}s) can be seen by visualizing the distribution of neutron flux in the cross-section of the reactor core radially. The number of flux neutrons moving inside the reactor core is depicted in a particular scale contour color distribution, as shown in Fig. 8. The neutron flux for the heterogeneous core of 3 fuel variations and 5 fuel variations was reviewed under two conditions, i.e. BOL (Beginning of Life) and EOL (End of Life). BOL conditions for reddish-orange 5 fuel variations are more evenly distributed in the core area than for 3 fuel variations. An even distribution will cause a high average neutron flux value in 5 fuel variations. The EOL conditions of the two heterogeneous cores have a similarity, at the end of combustion the neutron flux will concentrate into the central region of the reactor core ($F1$).

The rate of neutron production per second (neutron/s) by the fission reaction in the reactor is shown in Fig. 9. The neutron flux distribution affects the value of the fission rate. Similar to neutron flux analysis, the neutron production rate in one generation is visualized as a cross-sectional image of the XY axis (radial) with a specific color distribution and reviewed under BOL and EOL conditions. Fission rates at the beginning of the year are more evenly distributed than at the end of combustion for the entire fuel assembly. The heterogeneous core of 5 fuel variations in BOL conditions has a more even fission rate than the 3 fuel variations. This is shown in the even color gradation for the entire $F1$–$F5$ regions on the fuel channel 5 fuel variations. Meanwhile, for the heterogeneous core with 3 fuel variations, there is a large enough fission reaction in the $F2$ region and causes peaking power in the region. The EOL conditions of the two heterogeneous cores have a similarity, at the end of combustion the fission reaction will concentrate into the central region of the reactor core ($F1$).

The mass of the primary fuel product plutonium in GFR nuclear reactors decreases and increases over time, the burn-up is shown in Fig. 10. The burning phase causes a decrease in mass, while the breeding phase causes an increase in mass. The result of chain decay by U-238 has an impact on the mass increase of Pu-239. The fission product characteristics for the 5 fuel variations produce less mass at the end of combustion than the 3 fuel variations shown in Table 4.



a *b* *c* *d*

Fig. 8. Neutron flux: *a* – neutron flux distribution of 3 fuel variations of Beginning of Life condition; *b* – neutron flux distribution of 5 fuel variations of Beginning of Life condition; *c* – neutron flux distribution of 3 fuel variations of End of Life condition; *d* – neutron flux distribution of 5 fuel variations of End of Life condition

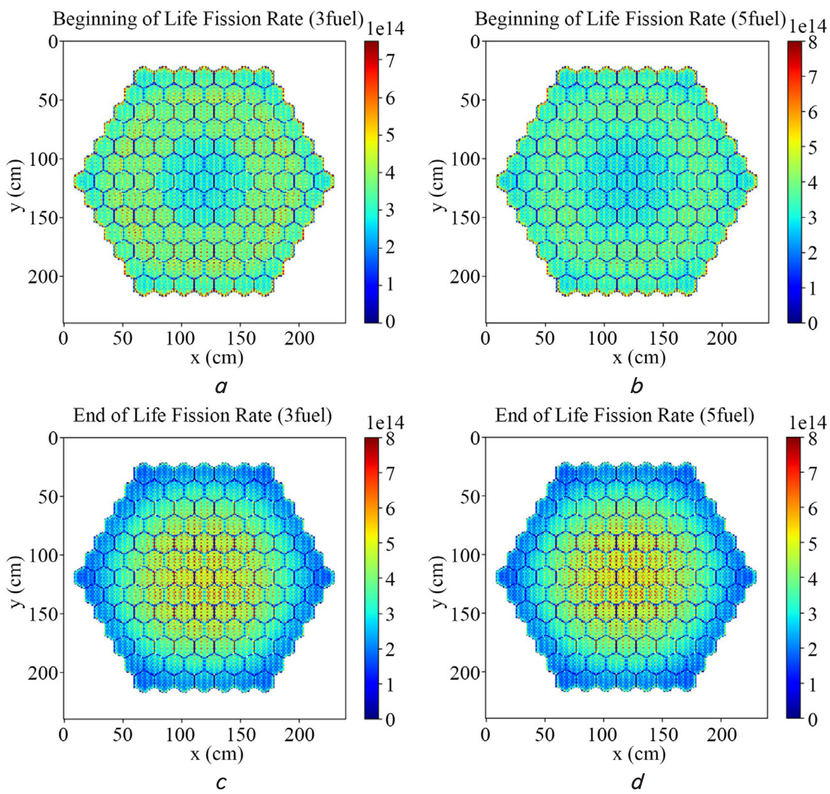


Fig. 9. Fission rate: *a* — fission rate of 3 fuel variations of Beginning of Life condition; *b* — fission rate of 5 fuel variations of Beginning of Life condition; *c* — fission rate of 3 fuel variations of End of Life condition; *d* — fission rate of 3 fuel variations of End of Life condition

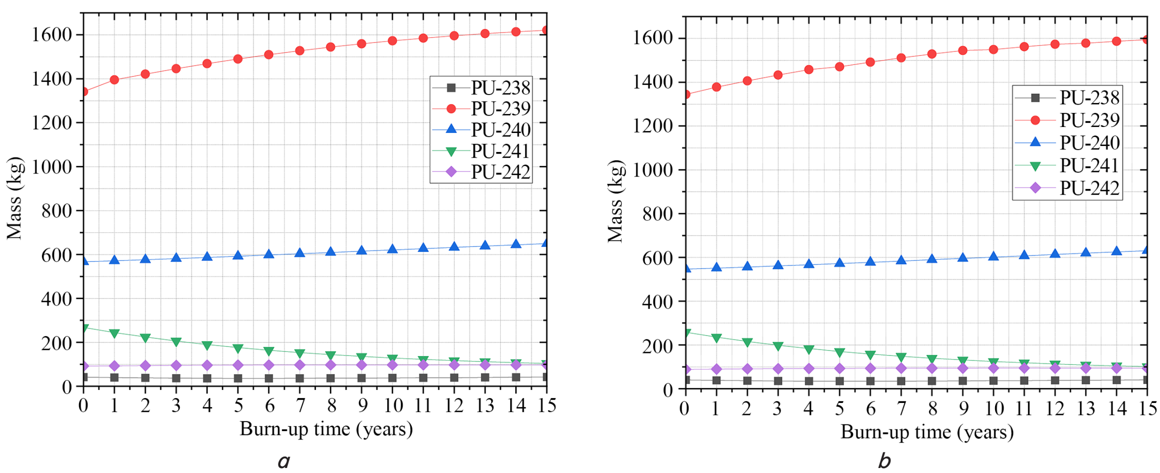


Fig. 10. Fission product of Pu of 3 and 5 fuel variations: *a* — fission product Pu 3 of fuel variations; *b* — fission product Pu of 5 fuel variations

Table 4

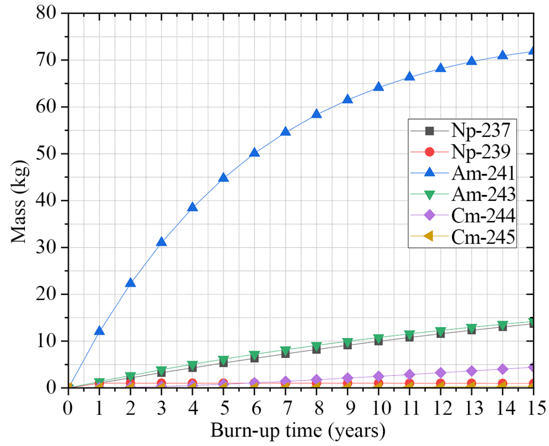
Mass of fission product plutonium

Heterogeneous core	Nuclides	Final burn-up mass (kg)
3 fuel variations	Pu-238	42.17
	Pu-239	1,620.88
	Pu-240	649.80
	Pu-241	104.25
	Pu-242	97.25
5 fuel variations	Pu-238	40.97
	Pu-239	1,589.86
	Pu-240	631.09
	Pu-241	101.47
	Pu-242	94.01

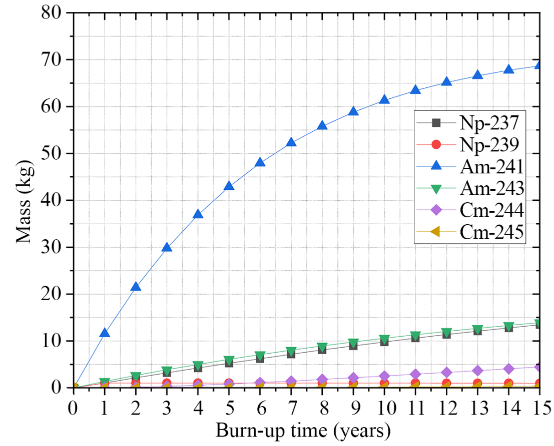
Table 4 shows that the highest and least amounts of Pu waste in the heterogeneous core of 3 fuel variations are Pu-239 and Pu-238, respectively. This applies equally to the heterogeneous core of 5 fuel variations, Pu-239 and Pu-238. The total waste mass of Pu is shown at least in the heterogeneous core of 5 fuel variations.

GFR reactor operating waste in the form of minor actinides in the form of neptunium, americium, and curium has the characteristics of high toxicity and long decay half-life. Almost all reactors produce minor actinide waste from spent fuel, that is plutonium.

The mass of minor actinides from early to late burn-up in heterogeneous core configurations increases, as shown in Fig. 11.



a



b

Fig. 11. Minor actinide waste for 3 and 5 fuel variations: *a* – minor actinide waste for 3 fuel variations; *b* – minor actinide waste for 5 fuel variations

Table 5 shows that the highest and least amounts of minor actinide waste in the heterogeneous core of 3 fuel variations are Am-241 and Cm-245, respectively. This applies equally to heterogeneous cores of 5 fuel variations, Am-241 and Cm-245. The total waste mass of minor actinides is at least shown in the heterogeneous core of 5 fuel variations.

Table 5

Mass of fission products minor actinides

Heterogeneous core	Nuclides	Final burn-up mass (kg)
3 fuel variations	Np-237	13.72
	Np-239	0.98
	Am-241	71.89
	Am-243	14.22
	Cm-244	4.40
	Cm-245	0.40
5 fuel variations	Np-237	13.46
	Np-239	0.98
	Am-241	68.70
	Am-243	13.93
	Cm-244	4.40
	Cm-245	0.40

Based on Table 4, the most Pu waste is found in the Pu-239 isotope. The depletion process that occurs every year causes the decay of the U-238 isotope into Pu-239 so that the mass of Pu-239 increases. Meanwhile, the most actinide waste is found in the isotope Am-241 shown in Table 5.

5. 3. Percentage variation of fuel volume fraction according to the desired criticality

The volume fraction is optimized using fuel variation with the best analysis results. The results of the previous analysis showed that 5 fuel variations ($F1=8$ %, $F2=9$ %, $F3=10$ %, $F4=11$ %, $F5=12$ %) became the most optimal design when viewed in terms of criticality value, neutron flux, fission rate, and fission product. This test aims to see the effect of volume fraction variations on reactor criticality. The results of the trend graph in Fig. 12 show that the fuel fraction of 60 % gets an optimal criticality value. The volume fraction of 45–55 % receives the result of a criticality value that tends to be sub-critical.

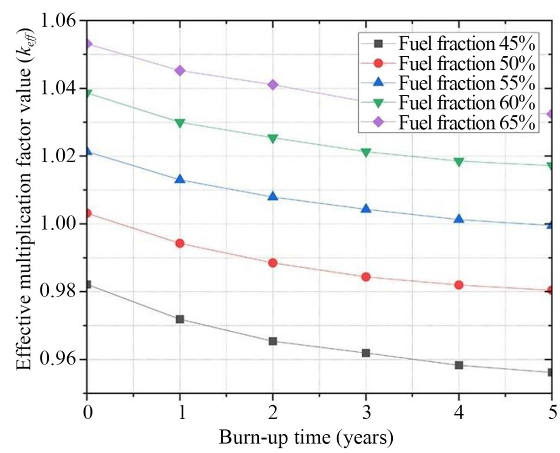


Fig. 12. UN-PuN volume fraction variation

Based on Fig. 12, UN-PuN fuel is absorbed by helium so that the probability of reacting fission becomes less than the maximum. The 65 % fuel fraction tends to have a reasonably high criticality value. It will impact reactor safety due to the extensive distribution of neutron flux.

6. Discussion on the use of a heterogeneous reactor core design with 3 and 5 fuel variations

The use of fuel composition (especially Pu) in the reactor core configuration greatly affects the level of criticality and distribution of neutrons produced. The results of the data obtained in this study show that the use of varied material compositions (heterogeneous) is better in terms of safety and criticality than the use of the same fuel composition (homogeneous). This is relevant to research [15], which showed optimal criticality levels and more even neutron flux distribution in heterogeneous core designs. Not only that, to ensure a better level of criticality and addressability, experiments are needed for several variations in fuel composition in the heterogeneous core of the GFR reactor. The novelty in this research is that researchers used a comparison method for 2 different main cases, i.e. 3 and 5 fuel variations.

Based on Fig. 6, the heterogeneous core with 3 fuel variations at the beginning of the combustion year has the highest k_{eff} value of 1.078, while at the end of the combustion year, it has a value of 1.037. The heterogeneous core with 5 fuel variations at the beginning of the combustion year has the highest k_{eff} value of 1.047, while for the end of the combustion year, it has a value of 1.013. The heterogeneous core of 3 fuel variations has the characteristics of a criticality value that tends to be higher than the heterogeneous core of 5 fuel variations. Heterogeneous core case data 3 fuel variations have the most optimal and stable criticality values, i.e. at the percentage of plutonium $F1=8$ %, $F2=10$ %, and $F3=12$ %. Meanwhile, for heterogeneous core case data, 5 fuel variations in the percentage of plutonium $F1=8$ %, $F2=9$ %, $F3=10$ %, $F4=11$ %, $F5=12$ %. The excess reactivity value of heterogeneous core case data 3 fuel variations is the most optimal and stable for the beginning of burn-up of 5.40 % and the end of combustion of 2.84 %. The excess reactivity value of heterogeneous core case data 5 fuel variations is the most optimal and stable for the beginning of burn-up of 3.72 % and the end of combustion of 1.69 %. The heterogeneous core design of 5 fuel variations can reduce the excess reactivity value by up to ±2 % at the beginning of the burn-up year.

Good criticality in core 5 fuel variations also applies to the result of extending the burn-up period to 15 years (Fig. 7). The heterogeneous core of 5 fuel variations with the composition in the year 5 to year 15 year graph trend is slower than the heterogeneous core of 3 fuel variations. A good material breeding process can maintain criticality until the end of combustion. Material U-238 captures one neutron to become U-239, which then undergoes beta decay to become material Np-239. Np-239 material undergoes beta decay back into Pu-239 material, which is classified as fissile fuel.

The level of criticality will affect the neutron flux distribution, fission rate, and fission product. The more evenly distributed the neutron flux, the longer and more stable the neutron lifespan (Fig. 8). Neutrons can move towards other isotopes to produce new neutrons from fission chain reactions. The reddish-orange color indicates that neutrons that carry each unit area per second have a relatively high number and intensity. EOL conditions have similar flux distribution characteristics between the two designs. Both fuel variations in the reactor's center are solid red, indicating the distribution of neutron flux centered to the center as the burn-up time passes. The average value of neutron flux for 3 fuel variations at BOL and EOL conditions is 1.091×10^{10} neutrons/cm^{2}s and 9.924×10^{9} neutrons/cm^{2}s. Meanwhile, for 5 fuel variations in a row 1.107×10^{10} neutrons/cm^{2}s and 9.990×10^{9} neutrons/cm^{2}s.

The heterogeneous core of 5 fuel variations BOL condition fission rate equalization is better than 3 fuel variations (Fig. 9). EOL conditions are similar to neutron flux distribution. The heterogeneous core of 5 fuel variations shows the most stable decrease in the average fission rate. This can be seen by comparing the gap between the average value of the fission rate at the beginning of the year and the end of the combustion year. The average fission rate of 3 fuel variations in BOL and EOL conditions is 9.306×10^{13} neutron/s and 8.899×10^{13} neutron/s. Meanwhile, for 5 fuel variations consecutively 9.196×10^{13} neutron/s and 8.894×10^{13} neutron/s. The existence of a good breeding process by the decay of U-238 material into Pu-239 has an impact on the average value of the fission rate, which does not decrease drastically.

Based on Fig. 10, the heterogeneous core of 5 fuel variations produces less mass of plutonium material products from combustion. It can realize one of the main objectives of fast reactors in the form of GFR discussed by GIF, that is proliferation resistance or misuse of fuel for nuclear weapons in the future. In addition, the results of GFR reactor operations also produce minor actinide waste (Fig. 11). High production waste is found in Am-241, Am-243, and Np-237 materials. Fertile material in the form of Pu-240 undergoes beta decay and produces a new nuclear product in the form of Am-241 waste. In addition, Pu-242 also undergoes beta decay into Am-243 material. U-235 in the decay chain produces actinide waste in the form of Np-237. Heterogeneous cores with 5 fuel variations have less mass of minor actinide waste than the 3 fuel variations shown in Table 5. This can minimize the presence of minor actinide materials in the world because it has high toxicity properties and a long half-life (T1/2).

Additional analysis in the form of variations in the composition of the volume fraction of fuel needs to be carried out. Based on Fig. 12, the composition of the fuel volume fraction with a percentage of 60 % can produce the desired criticality level that is close to 1. Using percentages above and below 60 %, the criticality value obtained is still not close to 1 (sub-critical and super-critical). The percentage of 55 % is closest to 1, but at the end of the combustion the criticality value tends to be sub-critical. This needs to be avoided so that the reactor can operate for a long time.

Neutronic analysis resulting from both heterogeneous core designs using OpenMC calculations shows that heterogeneous cores of 5 fuel variations have good potential to be used as a reference for future GFR reactor research. This result needs to be developed again because this study has a limitation on the use of variations in fuel composition only in the radial direction (XY axis). The use of fuel variations in all directions (radial and axial) can provide more comprehensive neutronic analysis results.

7. Conclusions

1. The criticality value (k_{eff}) for the heterogeneous core design with 5 fuel variations is better and closer to 1 (critical) than for the heterogeneous core with 3 fuel variations for combustion periods of 5 years and 15 years. The heterogeneous core design of 5 fuel variations can reduce the excess reactivity value by up to ±2 % at the beginning of the combustion year.

2. The neutron flux characteristics for the 5 fuel variations are better and more evenly distributed when compared to the 3 fuel variations. Similarly to the fission rate, the 5 fuel variations can maintain the fission reaction rate well until the end of combustion. Fission products in the form of plutonium fuel from combustion and minor actinide waste in 5 fuel variations produce less mass than 3 fuel variations.

3. Fuel fraction UN-PuN of 60 % gets the optimal criticality value in the variation range of 45 % to 65 %.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Financing

This research was supported by Kementrian Pendidikan, Kebudayaan, Riset, dan Teknologi (KEMENDIKBUDRISTEK) Indonesia.

Data availability

The manuscript has associated data in a data repository.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

The authors thank Direktorat Riset, Teknologi, dan Pengabdian kepada Masyarakat for the support by Hibah Pascasarjana Penelitian Tesis Magister (PPS-PTM) 2023 with the agreement number No. 5453/UN25.3.1/LT/2023.

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